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Including N_2O in ozone depletion models for LCA

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Abstract
Purpose Recent literature has highlighted a renewed debate amongst the scientific community about the relevance of nitrous oxide (N_2O) emissions to future ozone layer management. This raises the question as to whether the life cycle assessment (LCA) community should also consider incorporating N_2O into its ozone depletion models. This discussion summarises a preliminary investigation into the justification for doing so.
Methods Literature on the atmospheric science of ozone depletion and N_2O was reviewed, in particular recent proposals for an ozone depletion potential (ODP) factor that can be applied to anthropogenic N_2O emissions. To identify their potential significance to life cycle impact assessment (LCIA) results, these ODP values were applied to both a wastewater management case study and global emissions inventories. The literature review was also used to highlight certain issues that need further consideration if N_2O is to be incorporated into LCIA models.
Results Atmospheric modelling has shown that continued anthropogenic N_2O emissions could substantially affect ozone layer recovery. Furthermore, N_2O now represents one of the biggest remaining opportunities for emissions abatement. The two steady state ODP factors for N_2O available in the literature are in close agreement, with one of the models used showing reasonable calibration to accepted ODP values for other substances. Analysis of the wastewater case study showed that the incorporation of these interim ODP values for N_2O could have a substantial impact on LCIA results interpretation. This finding should be equally relevant for other case studies where N_2O emissions play a prominent role.
Conclusions The inclusion of N_2O into marginal-impact LCIA ozone depletion models would seem justified, given the relevance of N_2O emissions to a number of planning debates in which LCA currently has a prominent role. If this is not pursued, then the use of LCIA to support decision-making could mask, rather than reveal, an issue that may be environmentally relevant. Published ODP values for N_2O could be used as an interim measure. However, they are dependent on assumptions that may not be the most relevant choice for application to LCA studies. Further investigation is therefore required on how best to specify a range of ODP values for N_2O that can support robust sensitivity analysis in LCIA. Fortunately, the state of atmospheric modelling science would seem sufficiently mature to be able to inform this process. LCA-specific methodological challenges (e.g. choice of time frames, spatial implications) will also need to be addressed.

Keywords LCA · N_2O · Nitrous oxide · Normalisation · ODP · Ozone layer · Wastewater treatment

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1 Introduction

1.1 N_2O and the ozone layer

Atmospheric scientists have long recognised the damaging effect that nitrous oxide (N_2O) emissions can have on

the stratospheric ozone layer (Crutzen 1970; Johnston 1971; Kinnison et al. 1988). Although stable in the lower atmosphere and slow to break down upon reaching the stratosphere, N_2O is the main source of reactive nitrogen oxides that deplete global ozone concentrations at altitudes between 25 and 35 km. However, this risk was never formally recognised through inclusion in the list of substances targeted by the Montreal Protocol. International action to restore the ozone layer has instead focussed on chlorine- and bromine-containing compounds. These are more significant at other altitudes, plus are the dominant cause of the ozone layer hole over the polar regions (Chipperfield 2009).

Addressing N_2O emissions might seem a far less tractable problem for policy action than for the higher profile chlorinated and brominated compounds. The main concerns in the latter group are anthropogenic emissions that were, in many cases, relatively easy to target (through their association with specific technologies) and curb or eliminate. In contrast, the IPCC (2007) estimates that less than 40% of global N_2O emissions are from anthropogenic sources, with the majority of these generated from biological processes that are stimulated by nitrogen inputs to agricultural lands (~16% of total) and subsequently to waterways (~10% of total). These emissions will be highly dispersed, highly variable and difficult to estimate. Further, their association with food production means that management change is not likely to come easily or rapidly.

However, this is not a good reason to ignore the issue. Modelling by Ravishankara et al. (2009) suggests that anthropogenic N_2O emissions are currently the greatest source of human-induced stratospheric ozone layer damage. Given that the remaining stockpiles of ozone-depleting halocarbons will progressively be exhausted, and global N_2O emissions are likely to remain steady or grow, they also show that anthropogenic N_2O may become the dominant ozone depletion potential (ODP)-weighted emission in the future. Daniel et al. (2010) confirmed that, when the effects are integrated over the remainder of the 21st century, reducing anthropogenic N_2O emissions could be an effective way of expediting ozone layer recovery. It is worth noting, however, that the benefits possible from N_2O mitigation are small compared to those already delivered through ratification of the Montreal Protocol (Daniel et al. 2010). Nonetheless, there are now a number of studies (Daniel et al. 2010; Eyring et al. 2010; Plummer et al. 2010; Ravishankara et al. 2009) indicating that a continuation of anthropogenic N_2O emissions could delay and/or alter ozone layer recovery. In line with this, the most recent Scientific Assessment of Ozone Depletion by the World Meteorological Association (WMO 2011) has for the first time included substantive coverage of the implications for ozone layer protection from N_2O emissions.

1.2 The role of LCA

These recent findings may well lead to increased attention from policy makers. In the meantime, however, the historical focus on managing chlorine- and bromine-containing substances would seem to have contributed to a lack of awareness amongst the broader community on the ozone-related risks associated with N_2O emissions.

While the life cycle assessment (LCA) methodology is widely used to introduce environmental issues that would otherwise be overlooked in the decision-making process, it typically does not address this particular concern. The most common life cycle impact assessment (LCIA) midpoint-level models for ODP are reasonably consistent in their treatment of chlorine- and bromine-containing substances and use of World Meteorological Organization (WMO)-recommended ODP factors,[1] but none consider the potential for ozone layer damage caused by emissions of N_2O (ECJRC 2010). This consistency no doubt reflects the strong historical consensus on the need to mitigate emissions of chlorine- and bromine-containing substances and on the ODP metrics to inform policy responses. However, scientific comment (Chipperfield 2009; Wuebbles 2009) and literature (Daniel et al. 2010; Eyring et al. 2010; Plummer et al. 2010) following the Ravishankara study shows that debate is unresolved on the issue of N_2O emissions management.

From our perspective as users of LCA, we therefore feel that the exclusion of N_2O (from ODP models) compromises two of the fundamental benefits that LCA can offer. The first is that it provides quantitative analysis across a broad spectrum of environmental concerns, thereby providing a robust framework for including *as many environmentally relevant issues* as possible into the decision-making process. Secondly, it does this using best-estimate models of marginal impact developed with *as much scientific rigour as is possible* in each case. LCA does not provide environmental impact assessment in the strict sense, as this requires a higher level of certainty about the extent of environmental or human health damage. Rather, we see its role is to provide credible perspective on the *possible* impacts associated with a broad range of activities across the full life cycle of the products or services in question.

2 Case study application

Ravishankara et al. (2009) postulated that an ODP factor for N_2O emissions might be 0.017 kg CFC-11e/kg N_2O, much

[1] Most of the publicly available LCIA midpoint models use ODP factors taken from the 2002 WMO Scientific Assessment (Montzka et al. 2003) and have not yet incorporated the ODP changes recommended in the 2006 (Daniel et al. 2007) or 2010 (Daniel et al. 2011) scientific assessments.

lower than for most CFCs, but at a similar level to some HCFCs that are being phased out under the Montreal Protocol. Using a different model but for the same atmospheric conditions, Daniel et al. (2010) subsequently calculated a value of 0.019 kg CFC-11e/kg N_2O. To our knowledge, these are the only two literature examples of detailed atmospheric modelling being distilled into ODP values for N_2O. In doing so, they have made it possible to review the significance of this issue to LCA results. While we are not the first to identify this opportunity (see Andrae and Andersen 2011), we are not aware of any other studies that have done so in a quantitative manner. We have therefore incorporated an ODP factor for N_2O emissions into our LCIA analysis, using 0.018 kg CFC-11e/kg N_2O as the average of these two reported values.

Taking the normalisation inventories used for the ReCiPe LCIA method (Goedkoop et al. 2009; Sleeswijk et al. 2008), inclusion of this factor for N_2O would increase the ODP estimate for the overall global and European economies by 198% and 455%, respectively. Such a large change suggests that LCA results for case studies involving N_2O emissions in the foreground inventory may change substantially. Amongst others, this could affect studies on agriculture, forestry, land use change, biofuels, wastewater management and certain industrial processes.

More broadly, it could affect any studies that do (or should) include the ODP impact category and, to assist in interpreting the study results, use a normalisation step based on economy-level impact estimates. This would typically involve the case study's ODP impact score being divided by the ODP impact score for the chosen benchmark economy, so as to give some perspective on the scale of the case study result. As demonstrated above, the inclusion of N_2O will lead to large increases in the economy-level ODP estimates and therefore the denominator of this calculation. This would mean a significant decrease in the normalised score for any case study that does not itself involve significant levels of N_2O emissions. However, for those industries where N_2O emissions are likely to be substantial, the opposite effect on the normalisation process might be expected.

As an example of the latter, Fig. 1a demonstrates that including an ODP factor for N_2O can make this issue look much more significant for LCIA of an urban sewage treatment plant (STP). Here, the STP inventories are taken from Foley et al. (2010), with the midpoint impact results benchmarked against ReCiPe's estimate of the LCIA burden for the global economy. For an STP with marine discharge of treated effluent containing a total nitrogen (TN) concentration of 10 mg/L, the default ODP result ranks 16th out of 18 impact categories and is three to four orders of magnitude lower than those for Marine Eutrophication Potential and Global Warming Potential. Notwithstanding concerns about hidden bias in drawing such a conclusion (Heijungs et al. 2007), this result implies that the STP contribution to the global ozone depletion 'problem' is trivial compared to its contributions to other environmental challenges. However, if the proposed ODP factor for N_2O is included in the assessment, then the STP's contribution to global ODP ranks 4th and is on a par with those emerging issues (e.g. global warming, ecotoxicity) already of some concern to urban water system planners.

Figure 1b then illustrates how the inclusion of N_2O in ozone depletion considerations could affect LCIA-based decision-making when options are being compared. In this instance, we explore tradeoffs associated with the inexorable push to improve waterway health in Australian urban areas by reducing STP effluent nutrient levels. Environmental debate on such a decision would typically extend no further than the consideration of greenhouse gas implications. For scenarios 5 and 6 of Foley et al. (2010), reducing the TN

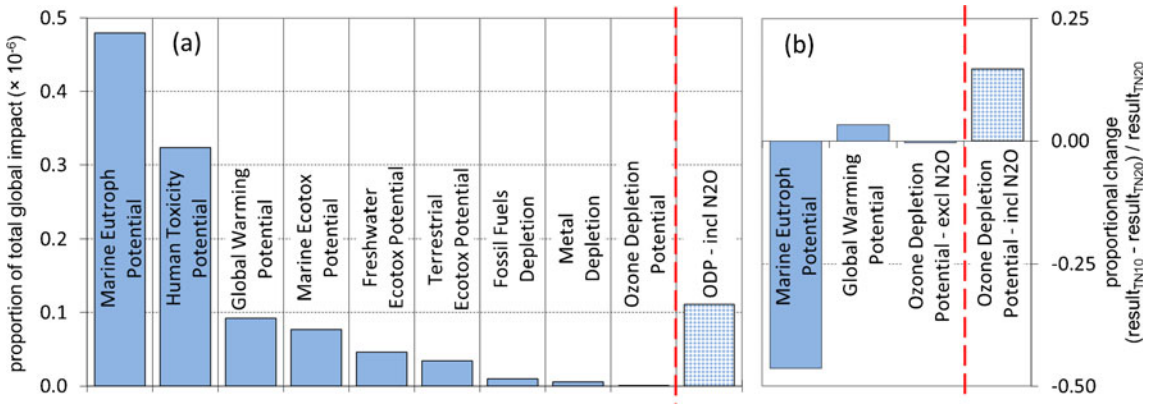

Fig. 1 Selected midpoint LCIA results applying the ReCiPe midpoint (H) method to STP scenarios 5 and 6 from Foley et al. (2010). The ODP results are compared with/without the inclusion of an ODP factor for N_2O (0.018 kg CFC11e/kg N_2O): in **a**, on an absolute basis for a scenario with total nitrogen (TN)=10 mg/L, normalised against global impact estimates, and in **b**, as a proportional change caused by a reduction in effluent TN from 20 to 10 mg/L

concentration in the effluent from 20 to 10 mg/L increases the estimated life cycle N_2O emissions by 19%. However, because of the significant GWP contribution from power use and other sources, the associated increase in Global Warming Potential is very minor compared to the reduction in Eutrophication Potential. This result would suggest only a negligible trade-off and therefore great benefits in moving to the lower effluent nitrogen concentration.

While consideration of the default ODP results would do nothing to change the conclusions drawn, inclusion of an ODP factor for N_2O may. Figure 1b shows that doing so would not only change the ranking of the two scenarios in terms of ODP but also identifies a potentially significant downside to the advanced nutrient removal. While real-life decision-making would of course be more complex than this simplified example, it does illustrate that ozone depletion results could possibly affect planning outcomes when there are substantial N_2O emissions involved.

3 Conclusions and recommendations

The presence of a notable quantitative result for ODP, whether normalised against economy-level or business-as-usual benchmarks, does not in itself confer environmental relevance. If this is a debate of little consequence because the ozone layer 'problem' has been resolved, then it would be reasonable to exclude or downplay the ODP results in most LCA case studies. However, our reading of the scientific literature is that this can no longer be considered the obvious position to take. Furthermore, the dominant paradigm in LCA is to use impact models based on estimates of marginal change (Huijbregts et al. 2011). If LCA practitioners choose (for good reason or bad) to consider midpoint ODP results, then it would seem beneficial to account for N_2O as a significant marginal risk under current circumstances.

If ODP models in LCIA are to include N_2O, then our review has highlighted five important issues that will need to be addressed.

1. If N_2O comprises a major contribution to ODP results, there will be a strong imperative for LCA practitioners to utilise high-quality N_2O emissions data. Given the large uncertainties associated with estimation from the majority of N_2O emission sources, this will not be a trivial exercise. Fortunately, research efforts in this area have accelerated in recent times thanks to growing interest from a greenhouse gas perspective. For the continental or global level inventories used in LCIA normalisation, emission estimates might more easily benefit from calibration against measured atmospheric concentration changes. Given recent developments in this regard (Corazza et al. 2011; Thompson et al. 2011), there might be some benefit in reviewing whether the available normalisation inventories for N_2O can be improved.
2. An increased focus on ODP results in LCA should also prompt a review of normalisation inventories for other ozone-depleting substances. Major distinctions can be drawn on the timing of impacts associated with those substances still of concern to policy makers. Some (e.g. HCFCs) are still in production with significant delays expected before the full emission discharges are exhausted; others already banned (e.g. CFCs and halons) will continue for some time as a source of emissions from the 'bank' of chemicals stored in products manufactured in the past, while others (e.g. CH_3Br and CCl_4) are more akin to instantaneous emissions from ongoing activities (Daniel et al. 2010, 2007). This variation in emission time lags introduces a significant methodological choice for LCIA normalisation inventories that are typically determined for a specific reference year. For example, LCIA normalisation against benchmarks based on reference year *emission* estimates (e.g. Bare et al. 2006; Lautier et al. 2010) may give very different perspectives to those based on reference year *production* estimates (e.g. Laurent et al. 2011; Sleeswijk et al. 2008).
3. Further investigation would be required to finalise the setting of N_2O characterisation factors in the midpoint ODP models used by LCA practitioners. Some confidence is provided by Ravishankara et al. (2009), whose calculated ODPs for CFC-12 (1.03) and HCFC-22 (0.06) were close to the WMO-recommended values at the time (1.00 and 0.05 respectively). Also, both the published ODP factors for N_2O were generated with steady state modelling for N_2O (Daniel et al. 2010; Ravishankara et al. 2009), consistent with the favoured approach in LCA. However, the models employed were not strictly the same as those used to generate the WMO-recommended ODP values and, by inference, the other ODP characterisation factors commonly adopted in LCIA. The relevance of their methodologies to LCA application therefore warrants closer scrutiny.
4. Furthermore, predicting the long-term potency of N_2O will depend on forecasts for a range of extenuating factors. For example, the net ODP of N_2O will be influenced by atmospheric chlorine concentrations—the values presented above (0.017 and 0.019 kg CFC-11e/kg N_2O) were both calculated for atmospheric conditions in the year 2000, at which time the stratospheric concentration of reactive chlorine was very near its historical peak (Austin et al. 2010; Clerbaux et al. 2007). But Ravishankara et al. (2009) also calculated that the ODP for N_2O would be 50% higher if stratospheric chlorine concentrations were at pre-industrial levels.

Modelling by Austin et al. (2010) suggests this may occur around the end of the century, meaning that current atmospheric conditions may not be that relevant for time-integrated LCIA modelling based on long-term (100 years or greater) time frames. A contrasting example is climate change, which will have a dampening effect on the ODP of N_2O. Plummer et al. (2010) show that, with moderate growth in greenhouse gas emissions to 2100 following the SRES A1B scenario of the IPCC (2007), the resulting atmospheric temperature changes would reduce by more than 50% the expected increase in atmospheric reactive nitrogen caused by N2O emissions.[2] The modelling of ODP characterisation factors for use in LCA should therefore be based on choices (e.g. time frames and emission scenarios) that are consistent with those underpinning the modelling of (a) ODP values for other substances and (b) characterisation factors for other LCA impact categories.

5. Finally, there is also a need to consider the implications for endpoint-level LCIA metrics. Along with any debate on the inclusion (or otherwise) of N_2O, there may be additional challenges of relevance. The calculation of ODP values is based on changes to *integrated global* ozone concentrations; however, the human health and environmental implications will be dependent on the *spatial distribution* of the ozone concentration changes. This relationship (between changing global concentration and the distribution of the changes) is fundamentally different for N_2O than for emissions of other ozone-depleting substances (Ravishankara et al. 2009). An obvious example of this is the negligible contribution made by N_2O to the extreme ozone layer thinning over polar regions. Further investigation is required on how best to include N_2O into the available endpoint LCIA models.

While there will clearly be some challenges in resolving the way forward on the issue of N_2O and ozone depletion, one of the strengths of LCA is its ability to accommodate such knowledge hurdles in a transparent way. As an example, the ReCiPe method provides up to three different sets of impact models for each environmental issue, with each set encapsulating a different approach to uncertainty at the science/policy interface. The first set typically has a shorter-term focus, the second occupies the middle ground and aims to reflect the most common policy principles, while the third takes a more precautionary perspective by including impact pathways that are considered less certain. Maybe it is not that big a leap to get scientific input on a *range* of ODP characterisation factors that could be included for N_2O emissions in LCA studies.

Doing so would then allow decision-makers to test the sensitivity of their LCA results to this issue, with the confidence that their approach reflects the best *available* scientific thinking. Not doing so risks the perverse outcome whereby the use of LCA would reinforce, rather than challenge, the common perspective that the ozone depletion problem has largely been 'fixed'. And since LCA will continue being used regardless—often to inform and justify decisions that have long-term ramifications—the interim inclusion of N_2O in LCA ozone depletion models would at least encourage decision-makers not to overlook this potentially significant issue.

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